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A TIGHT UPPER LIMIT ON OSCILLATIONS IN THE AP STAR ϵ URSAE MAJORIS FROM *WIRE* PHOTOMETRY

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ABSTRACT

Observations of ϵ UMa obtained with the star tracker on the Wide Field Infrared Explorer (*WIRE*) satellite during a month in mid-2000 are analyzed. This is one of the most precise photometry of an Ap star. The amplitude spectrum is used to set an upper limit of 75 parts per million for the amplitude of stellar pulsations in this star unless it accidentally oscillates with a single mode at the satellite orbit, its harmonics or their one day aliases. This is the tightest limit put on the amplitude of oscillations in an Ap star. As the rotation period of ϵ UMa is relatively short (5.1 d), it cannot be argued that the observations were made at a wrong rotational phase. Our results thus support the idea that some Ap stars do not pulsate at all.

Subject headings: stars: individuals (ϵ UMa)—stars: oscillations

1. INTRODUCTION

The excitation of pulsations in the lower part of the classical instability strip is still far from being understood. Some normal stars in this category show δ Scuti pulsations while others do not, and those that do pulsate only do so in a seemingly random subset of possible modes. Among the chemically peculiar stars, the so-called Ap stars that are the subject of this Letter, there is a similar puzzling division between the rapidly oscillating Ap stars (roAp stars) and the non-oscillating variety (noAp stars). This has lead some to propose that oscillations are present in noAp stars but at an undetectable level. Here we report one of the most precise photometric observations to date on an Ap star, which provides a strong upper limit on oscillations.

The Ap stars have peculiar spectra, with lines from elements such as Silicon, Magnesium, Mercury, Chromium, Europium and Strontium. The roAp stars have pulsations with periods about 5–15 min and typical amplitudes of a few milli-mag (Kurtz 1982, 1990; Kurtz & Martinez 2000). So far, thirty two objects have been classified in this subclass (Kurtz & Martinez 2000; Kurtz, personal communication). For recent theoretical works on the oblique pulsator model and the excitation mechanism in roAp stars see Bigot et al. (2000), Cunha & Gough (2000), Balmforth et al. (2001) and Bigot & Dziembowski (2002).

A detailed study of the differences between roAp and noAp stars was carried out by Hubrig et al. (2000). They found that as a group, the roAp stars are 0.57$\pm$0.34 mag brighter than the zero-age main sequence (ZAMS) while noAp stars are 1.20$\pm$0.65 mag above the ZAMS, which suggests that the latter are slightly more evolved than the roAp stars. It has also been proposed that an overabundance of the rare earth elements Nd and Pr may be a signature of roAp stars (Cowley & Bord 1998; Weiss et al. 2000; Ryabchikova et al. 2001, 2002). Kochukhov et al. (2002) suggested, on the other hand, that all Ap stars in a certain temperature range pulsate and that the observed difference between roAp and noAp stars comes from the amplitude of the pulsation (i.e., it is simply below detectability in noAp stars).

A key point in testing this last suggestion is to press down the observational upper limits on the pulsation amplitudes in noAp stars. Kurtz et al. (2003a) observed the Ap star HD 965 over 2.7 h using a 2-m telescope and put an upper limit of 0.2 milli-mag or $\sim$200 parts per million (ppm) on the amplitude of oscillations in the *B*-band. This is the lowest limit for pulsation in a noAp star in the literature. However, the rotation period of HD 965 is uncertain and believed to be longer than two years. Kurtz et al. (2003a) thus concluded that, although it is likely that HD 965 is a noAp star, their observations cannot reject the possibility that it is nevertheless a roAp star. The reason is that according to the oblique rotator model, the amplitude of the oscillation is higher near maximum of the rotational modulation and may become zero at other phases (Kurtz 1990). Therefore, Kurtz et al. (2003a) stated that further observations of this star over a few years are required to substantiate its status as a noAp star. Here we report observations of the Ap star ϵ UMa, whose rotation period is short enough to avoid this problem.

ϵ UMa (HR 4905 = HD 112185) is classified as an A0p Cr star (Bohlender & Landstreet 1990). Its effective temperature and radius were estimated as $\sim$9000K and $\sim 4R_{\odot}$ (Pyper & Adelman 1985; Shallis & Blackwell 1979). At V=1.8 it is the brightest Ap star in the sky, but it is not known to pulsate.

A period of 5.0887 d was detected by Guthnick (1931) in absorption line intensities of ϵ UMa and was confirmed by further photometric and spectroscopic studies (Struve & Hiltner 1943; Provin 1953; Woszczyk & Jasinski 1980; Woszczyk & Michałowski 1981). Provin (1953) found that the variation has a double wave structure with the two maxima being separated by half the period. The periodicity is understood as the rotation period of the star, but the strength of the magnetic field is still uncertain (Rice & Wehlau 1990; Donati et al. 1990; Bohlender & Landstreet 1990).

2. OBSERVATIONS AND REDUCTION

After the failure of the main mission of the Wide Field Infrared Explorer (*WIRE*) satellite, launched by NASA in March 1999, its star tracker was successfully used for photometry of

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bright stars (Buzasi et al. 2000; Buzasi 2002; Poretti et al. 2002; Cuypers et al. 2002; Retter et al. 2003).

The detector is a 512 ×512 SITe CCD with 27 μm pixels; each pixel corresponds to ∼1' on the sky. The camera is unfiltered and the effective response is roughly $V+R$. The observations of ϵ UMa were obtained in the period 2000 June 22 – July 21, with a cadence of 0.5 seconds. Data reduction was done by applying a simple aperture photometry algorithm, which involved summing the central 4×4 pixel region of the window of 8×8 pixels that can be read. The background level, due mainly to scattered light from the bright Earth, was estimated from the four corner pixels of each image, and subtracted. Following aperture photometry, any points deviating more than 2.5σ in mean flux, image centroid, or background level were rejected. The data points were then phased onto the satellite orbit, extreme points were rejected and the mean shape was subtracted. A final total of 5.7 million data points (out of about 6.1 million initial measurements) were obtained after applying these clipping procedures. Further details on the reduction method can be found in Retter et al. (2003).

3. ANALYSIS

The upper panel of Fig. 1 presents the smoothed light curve of ϵ UMa, where data from each satellite orbit have been binned into a single mean value, resulting in 308 points. Around JD 2451732 there are jumps of ∼10% in the brightness of ϵ UMa. A comparison with the background level and the location of the centroid of the star on the CCD at this time (Fig. 1, three lower panels) shows that the effect is instrumental. The light curve is also affected by this effect, but to lesser extent, around JD 2451720 and 2451738.

In an attempt to remove from the light curve the effect of minor shifts in the location of the star in the CCD and small changes in the background level, several decorrelation methods were tried (Brown et al. 1991; Robinson et al. 1995). However, unlike for the case of our observations of Arcturus (Retter et al. 2003), these techniques did not satisfactorily correct the light curve. The reason for this behavior might be that, unlike Arcturus (which stayed within ±0.03 pixel during the observing run), ϵ UMa moved several tenths of a pixel from orbit to orbit. Consequently, the linear or low-order polynomial approximation of sub-pixel sensitivity variations was not valid over the range occupied by the star.

Fig. 2 displays the smoothed light curve of ϵ UMa during the last two weeks of the observations, when the instrumental effects were minimal. The light curve clearly shows the presence of the 5.1-d rotation period (Section 1), which has a double-hump shape.

To search for oscillations (presumably around 10 min) in the data from the last two weeks of the run, the slow variation from rotation was first subtracted. The upper panels of Figs. 3 & 4 show the amplitude spectrum of this high-pass-filtered time series. The graph is dominated by strong peaks that correspond to the satellite orbit, its harmonics and, at lower amplitudes, their 1-d^{-1} aliases. The bottom panel in Fig. 4 shows the spectral window. The 1-d^{-1} aliases are much stronger in the data (relative to the satellite orbit and its harmonics) compared with the spectral window. This behavior indicates that the data show instrumental variations within orbits and also with a periodicity of a day, perhaps from variable reflection from Earth on the satellite. The second panels in the figures display the amplitude spectra after fitting and subtracting all these frequencies simultaneously.

All peaks in the residual amplitude spectrum (which are not harmonics or 1-d^{-1} aliases) have amplitudes below 75 ppm. Most of the highest remaining peaks are, however, close to the harmonics of the satellite orbit and all appear in the spectral window. We conclude that there are no oscillations with amplitudes above 75 ppm.

The possibility cannot be ruled out that the star oscillates with a single mode that falls exactly on the satellite orbit, its harmonics or their 1-d^{-1} aliases. We estimated the probability of this occurring by chance by dividing the typical width of the peaks (taken as the full-width at half maximum, which is set by the length of the observing run) by 16 d^{-1} (the satellite orbit, for higher amplitudes) and by 1 d^{-1} (for lower amplitudes, since the data suffer from 1-d^{-1} aliases). The probabilities are about 0.5% and 7%, respectively. In other words there is a 0.5% chance that it oscillates with an amplitude below ∼1800 ppm and a 7% chance for an amplitude below ∼250 ppm.

To check whether the star has stronger pulsations at a specific phase of the 5.0887-d rotation period (see Section 1), the data from the last two weeks of the run (after removing the variation of the rotation period) were divided into ten equal phase bins. The corresponding power spectra of the bins were consistent with the power spectrum of the whole data (Figs. 3 & 4) and no significant peaks were found (besides the satellite orbital frequency, its harmonics and their 1-d^{-1} aliases).

4. DISCUSSION

The *WIRE* photometry clearly shows that ϵ UMa is variable on time scales of a few days with a period of ∼5 days (Fig. 2). Our results confirm the previous detections of the rotation period (Section 1). The noise in our data is comparable to that in the highest precision photometry done so far on roAp stars obtained during several years (Kurtz et al. 1997) or by the WET collaboration (Kurtz et al. 2003b).

Of major interest is the question whether ϵ UMa pulsates or not. We found an upper limit of 75 ppm on oscillations in this star, unless by chance it has a single mode that falls on the satellite orbit, its harmonics or their 1-d^{-1} aliases. This, however, is very unlikely since roAp stars usually show several pulsation periods in their light curves (Kurtz 1990).

We note that the observations were done using an effective response of roughly $V+R$ (Section 2). The amplitude of pulsations in roAp stars decreases with wavelength (Kurtz & Medupe 1996; Medupe & Kurtz 1998; Medupe 2000). ϵ UMa may, therefore, pulsate with amplitudes larger than the limit given above in narrower and bluer bands. Using the detector response, a typical spectrum of an Ap star (Le Borgne et al. 2003) and Fig. 1 of Medupe & Kurtz (1998) we estimated that the limits we can put on the amplitude of pulsations in ϵ UMa are about 50% and 120% larger in V and B, respectively. Kurtz & Medupe (1996), Medupe & Kurtz (1998) and Medupe (2000) found that the phase of the modulation also depends on the wavelength. This effect is, however, relatively small and the phase shift between the optical filters is about 0.5 radians. Therefore, different colors are probably not anti-phased with each other and cannot cancel the effect of pulsations. Using simulations, we found that in our case the reduction of the amplitude by this effect is negligible (less than 3%).

The rotation period of ϵ UMa is relatively short at 5.1 d (Sections 1 & 3) and the *WIRE* observations covered several cycles of this periodicity. Therefore, it cannot be claimed that the non-

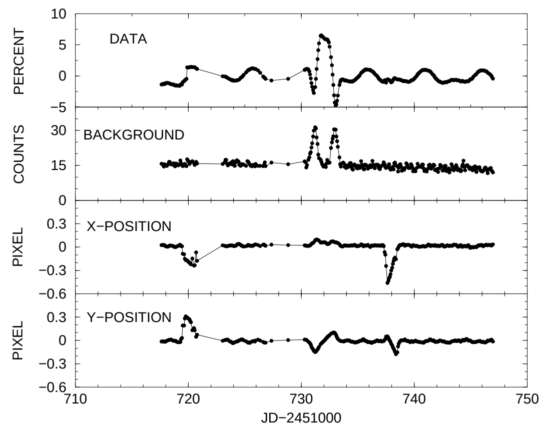

FIG. 1.— Upper panel: The light curve of ϵ UMa during the *WIRE* run in 2000 June-July. Each point represents a mean of about 18,600 0.1-s exposures obtained during a single 96-min orbit. Second panel: the background level. Third and bottom panels: the position of ϵ UMa on the CCD in the X- and Y-axis (in pixels), respectively, relative to the mean location of the star in the run (258.21, 259.66).

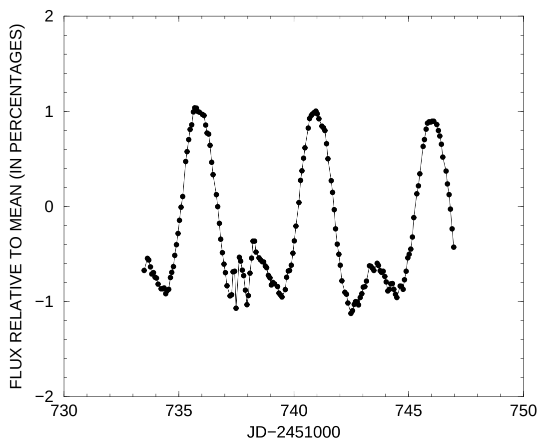

FIG. 2.— The light curve of ϵ UMa during the second half of the run, in which the instrumental effects have marginal influence.

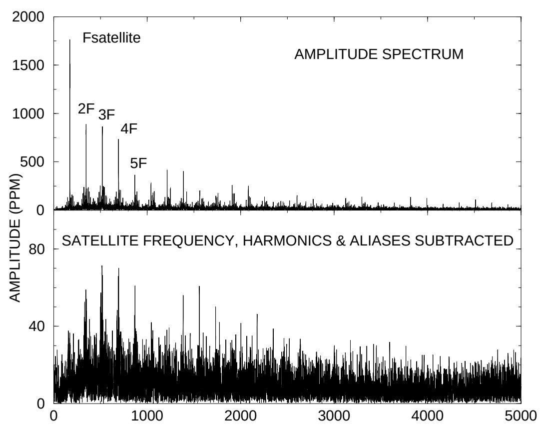

FIG. 3.— Upper panel: The amplitude spectrum of ϵ UMa during the last two weeks of the run, after the rotational variation was subtracted. Fsatellite is the satellite orbital frequency (173.6 μHz) and 2F, 3F... represent its harmonics. Bottom panel: The amplitude spectrum after subtracting variations at the satellite orbital frequency, its harmonics and their 1-d^{-1} aliases. Note the change in vertical scale.

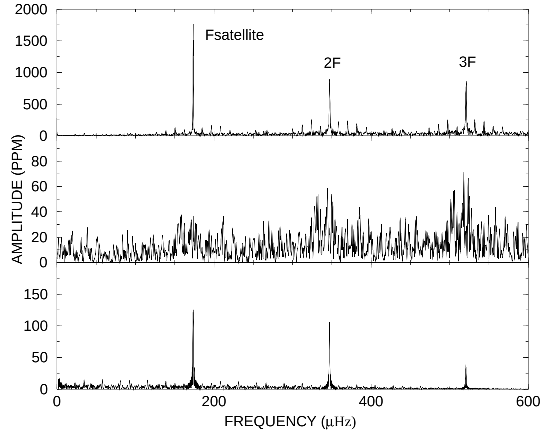

FIG. 4.— Same as Fig. 3 for the lowest frequencies. The presence of the 1-d^{-1} aliases around both the satellite frequency and its harmonics is evident. The lower panel presents the spectral window

detection of oscillations presented in this work is because of observations at a wrong rotation phase, which may be the case for noAp stars with long rotation periods (Section 1). In fact, we could not find oscillations at specific phases (Section 3). Our results thus suggest that ϵ UMa does not oscillate at all. It is interesting to note that it was proposed that an anomaly in the abundances of Nd and Pr may be a signature of roAp stars (Section 1). ϵ UMa does not have this anomaly and the null result on oscillations in this star thus supports this suggestion.

It was suggested that all Ap stars in a certain temperature range pulsate (Kochukhov et al. 2002). The temperature of ϵ UMa was estimated as $\sim$9000K (Section 1), which is slightly higher than the range of roAp stars – 7000–8300K (Kurtz 1990), although these limits are somewhat uncertain. It is therefore possible that the non detection of oscillations in ϵ UMa is simply because the star is too warm for the instability strip for roAp stars.

The question of whether noAp stars do pulsate with amplitudes below the detection limit is still open. Future space missions that significantly decrease the upper limit on the amplitudes of pulsations in these stars may give an answer to this question.

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